Improvement of the mass separation power of a cyclotron by using the vertical selection method

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IMPROVEMENT OF THE MASS SEPARATION POWER OF A CYCLOTRON BY USING THE VERTICAL SELECTION METHOD

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Abstract

It is well known that cyclotrons are very good mass separators, specially when the number of turns in the machine is large. This property is particularly interesting if the cyclotron unavoidably accelerates multiple species of radioactive beams simultaneously, which is the case for the cyclotron CIME at GANIL. We propose to improve the natural mass separation power by using a vertical resonance effect: it consists of putting two small electrodes between the poles, which provide a vertical electric field operating at two frequencies close to twice the RF frequency and which are tuned with respect to the vertical betatron oscillation. A prototype has been designed and built at GANIL, and tested successfully in the cyclotron CIME this September.

INTRODUCTION

In what follows, we will present successively the theory, the particle simulation, the prototype design, the first experiments and possible future improvements.

THEORY

Let's consider the vertical motion of a particle (q,m) in a cyclotron, where two electrodes are installed above and below the median plane, between the radii r_1 and r_2 near the extraction radius and with an angular extent $\Delta\theta$ (variable potential V, gap g). Introducing the vertical betatron oscillation parameter ν, the Dirac function δ, the azimutal second derivative, the RF harmonic h and the phase $\Delta\phi = h\Delta\theta$, we can write:

$$z'' + \nu^2 z = \alpha\ \delta \tag{1}$$

$$\alpha(t) = \frac{qV(t)}{gm\omega^2}\Delta\theta = \frac{V(t)}{g}\frac{\Delta\phi}{2\pi f_{hf} B_z} \tag{2}$$

In order to simplify the equations, let's consider the case ν=1/4 and introduce the constant one-turn transfer matrix T and the variable one-turn vertical "kick" matrices B_i :

$$T = \begin{bmatrix} 0 & 4 \\ -1/4 & 0 \end{bmatrix} \quad ; \quad B_i = \begin{bmatrix} 0 \\ \alpha_i \end{bmatrix} \tag{3}$$

A particle with the initial conditions $u_0=(z_0,z'_0)$ will have the following turn-by-turn transformation :

$$\begin{aligned}
u_1 &= Tu_0 + B_1 \\
u_2 &= Tu_1 + B_2 = -u_0 + TB_1 + B_2 \\
u_3 &= Tu_2 + B_3 = -Tu_0 - B_1 + TB_2 + B_3 \\
u_4 &= Tu_3 + B_4 = u_0 - TB_1 - B_2 + TB_3 + B_4
\end{aligned}$$

Due to the particular choice of ν, we see that the particle comes back to the initial conditions after 4 turns, if the vertical kicks are all equal. However, if we choose the successive kicks judiciously with respect to the natural oscillation of the particle, it's possible to make a powerful vertical resonance appear. Let's choose:

$$\theta_i = 2\pi i$$

$$\alpha_i = \alpha \sin(\nu\theta_i + \varphi) = \alpha \sin(\frac{\pi}{2} i + \varphi) \tag{4}$$

After $4n$ turns, we obtain:

$$u_{4n} = u_0 + 8\alpha n \begin{bmatrix} -\cos(\varphi) \\ \dfrac{\sin(\varphi)}{4} \end{bmatrix} \tag{5}$$

which shows that the vertical amplitude of the particle oscillation increases linearly with the number of turns.

If $1/\nu$ is not equal to 4 (or not integer), the demonstration is more sophisticated but the effect remains the same. Moreover, we can show that this resonance occurs for the particles having different initial conditions. In fact, this linear effect does not affect the emittance of the bunch.

Having in mind that we want to preserve the acceleration of the reference beam (well isochronised), and to deflect the other species (shifted in phase) verticaly, the best would be to multiply the time-dependant potential signal corresponding to (4) by a normalised square wave (stepped or not), denoted by *H(t)* :

$$V_{ideal}(t) = V_{\max} \sin(\frac{\nu}{h}\omega_{hf} t)\ H(t) \tag{6}$$

However, it is not technically straightforward to generate such a signal, so that for our prototype, we have replaced it by a sinusoidal one, with a frequency equal to $2f_{hf}$, in order to increase the efficiency at 45° instead of 90°, and with a tunable phase ψ (see also figure 1):

$$V(t) = V_{max} \sin\left(\frac{\nu}{h}\omega_{hf} t\right) \sin(2\omega_{hf} t + \psi) \tag{7}$$

$$= \frac{V_{max}}{2}\left(\sin(\omega_1 t + \psi + \frac{\pi}{2}) + \sin(\omega_2 t + \psi - \frac{\pi}{2}) \right)$$

$$\omega_1 = 2\omega_{hf}\,(1 - \frac{\nu}{2h}) \quad ; \quad \omega_2 = 2\omega_{hf}\,(1 + \frac{\nu}{2h})$$

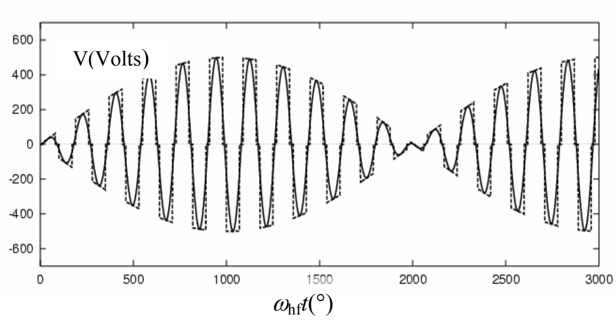

Figure 1: Ideal and realistic potential signals $V(\omega_{hf})$.

We conclude that two signals with frequencies close to $2f_{hf}$ and with the same amplitude must be generated on one of the electrodes, which requires a large bandwidth. Considering that the excited species are stopped on two horizontal slits separated by a gap g, we can also deduce an estimation of the potential needed:

$$V_{max} = \frac{2\pi}{16} \frac{g^2 f_{hf} B_z}{h\Delta\theta} \frac{1}{n} \tag{8}$$

PARTICLE SIMULATIONS

In order to check the theory, we have simulated the partical behaviour with our code LIONS [1]. We have chosen one of the available measured magnetic maps (B_z=1.5T, ν=0.269) and f_{hf}=11Mhz using the harmonic h=3. The results are in very good agreement with the equation (8) , so that we have fixed the objective of the prototype to V_{max}=500 V in order to preserve some margin. (figure 2).

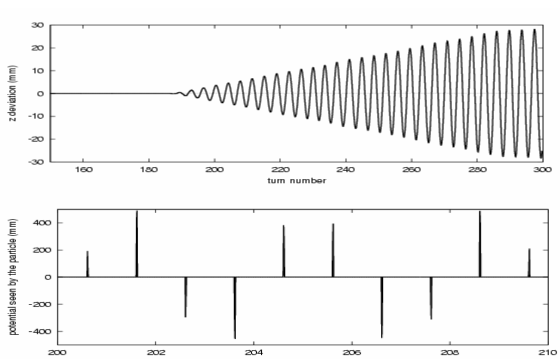

Figure 2: Typical vertical resonance trajectory (top) and applied potential between turns 200-210 (below).

PROTOTYPE DESIGN

Mechanics

The electrodes consist of two copper sheets (length=250mm, angle=5°, gap=18mm) mounted inside an open-ended aluminum box extended by a cylinder towards the vacuum-chamber flange (figure 3). The upper electrode is connected to the box, which is grounded and protects against exterior perturbations. The electrode below receives the RF signal from a 1.2mm wire, left at a constant distance from the ground box in order to keep the caracteristic impedance fixed (Z_c=240Ω, L=60cm). Two insulated copper plates at the entrance allow us to measure beam current losses. The whole device is installed in the hill gap of one cyclotron sector.

Figure 3: View of the prototype device with the upper part and electrode lifted off.

Signal generation and power circuits

In order to obtain the desired electric field between the electrodes, we have designed and installed a power circuit as indicated in figure 4: the driving signal (7) is generated in the control room, by mixing the second harmonic of the CIME RF signal (carrier port) and a frequency generator signal tuned at the "$\nu/2h$" value (local oscillator port). The center frequency rejection is better then 40 dB and the two needed frequencies have identical levels.

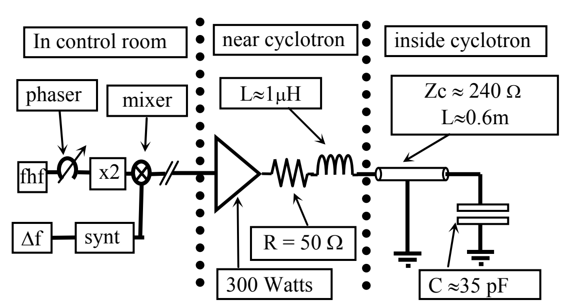

Figure 4: Power circuit and the electrodes.

As a high voltage and a large bandwidth are required, a resonant circuit with a low Q is necessary. Moreover, we need a solution with low losses inside the vacuum chamber, so that we don't have to cool it. The power circuit design is based on the series resonance of a quarter-wave resonant line loaded with the equivalent electrode capacitance (figure 4).

The transmission line is split into two sections in order to avoid some obstacles present in the vacuum chamber, and its length is shortened by a lumped inductance to use the vacuum feedthrough in a very low impedance region, already insensible to the characteristic impedance change. Out of the vacuum chamber a second inductance is used for fine tuning and a 50 Ω series resistor ensures the Q dumping and the impedance matching to the amplifier. The fine tuning is important to amplify the two signal components equally and to avoid distortion effects.

FIRST BEAM TESTS

We achieved the first beam test with our prototype this september. Due to a lack of available time, it was not possible to tune the machine with 2 simultaneous ion species close one to the other. The accelerated stable beam was $^{16}O^{5+}$ with F_{hf}=11.326Mhz, B_0=1.46 , h=2.
The procedure to induce and optimise the vertical resonance effect was very simple and took less than 15 minutes, the beam having been previously isochronised and extracted. We chose Δf=1.52Mhz, corresponding to the estimated ν_z=0.269. Then we shifted the phase of the signal between –90°and 90° in order for the loss peaks to appear (-45° and +45°), measuring them with the beam current probes. Then we tuned the phase to 45° and reoptimized the *Δf*. Once the resonance was obtained, we returned the phase to 0°, and checked that the beam went correctly through the device and through extraction. In order to simulate the presence of another beam, we applied a slight *ΔB/B* variation and checked that the beam was vertically deflected and stopped by the slits.

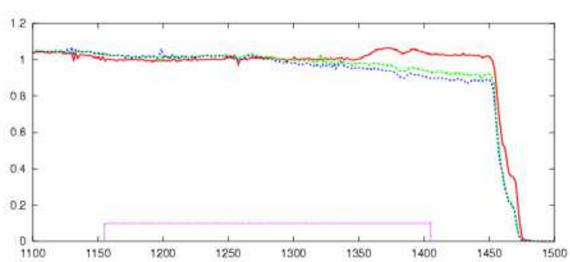

Figure 5: Normalised beam current as a function of the radius (isochronised) : red = no voltage, green ≈ 370V, blue ≈ 500 V, pink=position of electrodes.

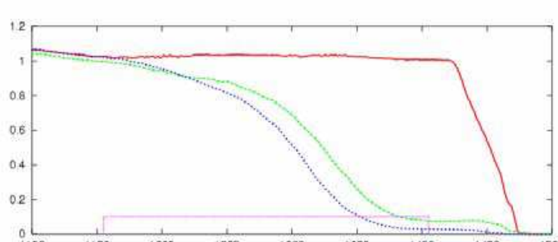

Figure 6: Normalised beam current as a function of the radius for a beam phase shift of 40° : red = no voltage, green ≈ 370V ,blue ≈ 500 V.

Figures 5 and 6 show that the resonance effect occurs efficiently and that the desired beam is not disturbed. In fact the main difficulty was to minimize the phase width of the beam itself, and reduce an unexpected precession probably due to rather approximate knowledge of the acceleration parameters (e.g. angle at injection). The direct consequence was that we needed more potential than expected to make the beam vanish vertically (around 500 Volts instead of 300).

POSSIBLE IMPROVEMENTS

The first tests suggest some future improvements:

- A capacitive pickup on the electrodes to let a simple tuning of the resonant circuit, giving equal peaks on both signals and avoiding some loss for the beam of interest.
- Adjustable slits to tune their gap and chose the separation efficency on line.
- A wide-band tunable circuit to cover the entire working diagram of CIME.
- New beam simulations to understand the effect of a bad precession on the resonance better.
- A water cooled resistance to increase the available voltage, and a more powerful amplifier.

CONCLUSION

We have proved experimentally that the Vertical Mass Separator concept works without any major difficulty, provided that the beam is tuned correctly.

We are convinced that with the improvements suggested and in the frame of SPIRAL 2, we could reach a mass separation of about 6.10^{-5} and eliminate a significant part of the isobaric pollutants.

One question could be: *what is the theoretical limit ?* In the ideal case of a “round beam” cyclotron, for which the “natural” mass separation could be 3.10^{-4} (as in CIME) and the phase extension of the beam could be ±2 degrees (as at PSI), the mass separation would be 2.10^{-5}. Note that the “round beam” concept can work for low intensity beams (e.g. RIBs) as proved in [2].

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